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Double-ECO model technologies for an environmentally-friendly manufacturing

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Abstract

There are many technologies related to ecology in the world; however, these technologies have not made much progress due to the large cost and low profit that they represent. Therefore, the "Double-ECO model" and environmentally-friendly [1] technologies were proposed as an alternative to current manufacturing methods. The "Double-ECO model" stands for "Ecology" or the interaction between environment and men, and "Economy" for the profit that can be made by following this model. Two examples in which the model was applied, were explored and investigated as "Double-ECO model technologies": "Cost-effective and eco-friendly grease lubrication using polymer" and "Forced cooling using mist of strong alkaline water". It was concluded from the experimental results that improvements in the environmental pollution, mechanical properties and cost parameters were achieved through the proposed model.

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Keywords: Eco-Friendly, Manufacturing, Grease, Lubrication, Strong Alkaline Water, Forced Cooling;

1. Introduction

Since the beginning of the 21st century, the importance to manufacture products in an environmentally-conscious way has been highlighted. In this regard, manufacturers not only need to conserve energy, but they also need to scrutinize in order to save resources and reduce environmentally-harmful pollutants. Nowadays, there are many researches related to the environmental impact of men [2], as well as countermeasures to reduce it [3]; however, these are still insufficient. Particularly, in the field of manufacturing, most machine tools highly depend on lubricating oil and grease to achieve a smooth drive and high accuracy positioning on the slider. This represents a large environmental problem, since in most cases the lubricating oils and greases are misused, introduced into the environment and generate undesired pollution [4]. he Consequently, the importance of developing new manufacturing ideas that take into account parameters such as high accuracy, high quality and a low environmental impact had been underlined. Hence, manufacturers will be in the need of daring plans, unique ideas and new technologies [5].

Therefore, even though the driving concept of this research was "Ecology", it also included other concepts related to the industrial sector. Among these concepts are: suitable cost of a machine tool, low running cost, low maintenance fee and high precision machining. Thus, this study was meant to achieve the application of the "Ecology" and multiple industrial sector-related concepts, in conjunction with the advances of production engineering technology. For instance, regarding machine tool technology, while restraint of the thermal deformation on a machine tool was attempted to achieve high accuracy and quality, it was at the expense of using costly equipment and a large quantity of electrical energy. Even then, those the countermeasures taken were not enough to satisfy this parameters [6]. As a result, a new model that unites the concepts of "Ecology" and "Economy" as an industry niche, and reconciles environment and men, was developed and denominated the Double-ECO model. Moreover, on this research two examples related to the model were investigated as "Double-ECO model technologies": "Lubrication using grease add polymer mexture" and "Forced cooling using strong alkaline water".

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2. Explanation of Double-ECO model technologies

The general idea for the Double-ECO technologies is explained through the following flowchart shown in Fig. 1. The first purpose of most ecology-related technologies is environmental protection, while their second purpose was the cost-profit considerations. Because of this, given the different national laws and policies, such technologies started to compromise the environment due to the cost implications. In the end, the first purpose would be neglected because of the high cost that they represent. Thus, environmentally-friendly technologies are slowly advancing.

First stage: Environmental impact countermeasure over a technology

↓

Second stage: Cost and profit for the countermeasure was calculated.

↓

Final stage: Compromise countermeasure due to cost implication (national laws and policies are used)

※Final stage differs largely from the first due to compromised countermeasures

(a) Conventional environmentally-friendly technology

First stage: Environmental impact countermeasure over a technology and its cost simultaneously developed

Support: Technologies from all science fields are used (Only technologies with proven safety and affordability are used)

↓

Final stage: Countermeasure safest, most-affordable and cost-effective alternative is decided

※Final stage do not differ from the first.

(b) General idea of the Double-ECO model technologies

Fig. 1. Explanation regarding the general idea of the Double-ECO model technologies with its "Ecology" and "Economy" considerations.

In contrast, the "Double-ECO model" technologies prioritizes simultaneously environment protection and cost-profit considerations so that no compromises are made at any time. Although it is very difficult to achieve this, recent environmentally-friendly technologies had made remarkable progress. The model proposed first solves the technical problems for the incorporation of such technologies as countermeasures over an existing manufacturing process, these countermeasures are selected from all the science fields available so that in the end the safest, most-affordable and cost-effective alternatives can be selected. At this point, the largest profit that is feasible is guaranteed so the countermeasure itself would not be compromised. In this regard, the Double-ECO model technologies would demand an extensive knowledge of the science and economics fields for a successful development. Therefore, the Double-ECO model is coherent with the intensity of production and with the highest cost-effectiveness in eco-efficiency.

3. Innovative technology developments using the Double-ECO model

3.1. Development of a cost-effective and environmentally-friendly permanent grease lubrication for machine tool sliders

In this case, a research regarding permanent lubrication using a mixture of grease and polymer for the machine tool sliders was developed and evaluated. Firstly, the mixture of grease and polymer was developed to present high cohesion properties. Characteristically, this kind of mixture of grease and polymer present a non-Newtonian behaviour which means it is capable to follow a moving element placed over it. In this research, it was considered that the lubrication mixture, given its high cohesion properties, could be collected around the moving slider of a machine tool and avoid any waste or pollutant present when using conventional grease-based lubricants. In this regard, the polymer used in the mixture was Polyethylene oxide PEO_{-8}; which is a harmless material towards men and environment. Particularly, the optimum mixture composition was determined through permanent lubrication experiments. Such experiments showed that the required polymer amount was just a few percent in weight at a very low cost, whereas the coefficient of friction of a mixture composed by grease with 3 % PEO_{-8} was very small (= 0.1) and its cohesion property very large. After this, it was considered that most machine tool sliders generate a huge amount of waste because the sliding part tends to leave a lubricant path behind during machining operations. As a response, a new double-roller device for attracting and holding the grease mixture for the entirety of the machine life was developed and denominated as "W-rollers". Accordingly, a schematic view of the W-rollers is shown in Fig. 2, while a 3D plan and a photograph of the grease distribution device with W-rollers used in the experiments are shown in Fig. 3. Specifically, W-rollers consists of an outside roller for collecting, holding and distributing the grease mixture and an

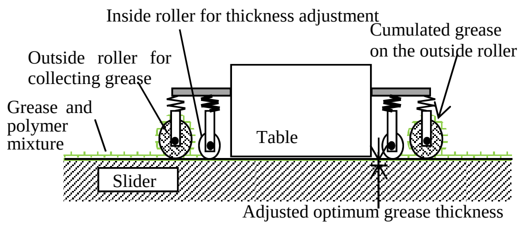


Fig.2. Schematic view of the W-rollers

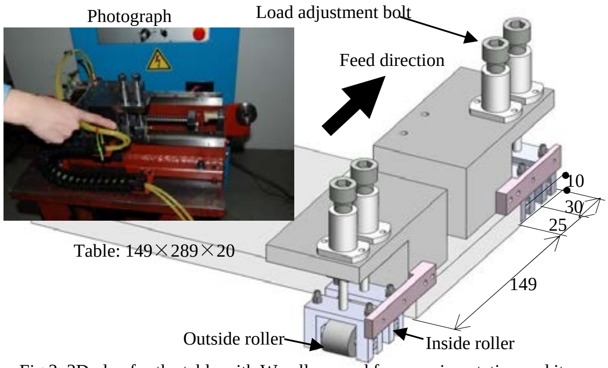


Fig.3. 3D plan for the table with W-rollers used for experimentation and its photograph

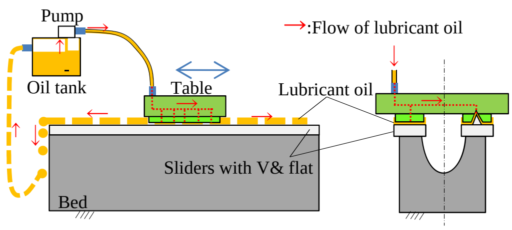


Fig.4. Schematic view of a conventional lubrication of machine tool sliders

inside roller for the grease thickness adjustment. In this way, four W-rollers were set over the slider in two parallel guideways and each guideway is composed of an arrangement of two W-rollers (= two W-rollers × two slider). A conventional lubrication of machine tool sliders is shown in Fig. 4.

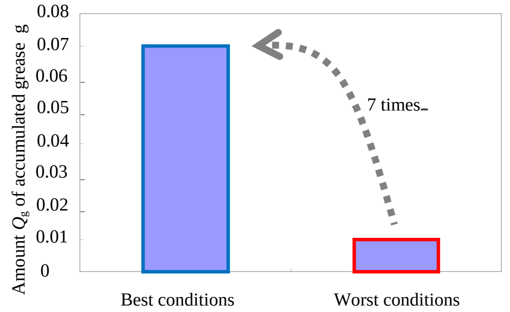
On the other hand, the optimum conditions for the W-rollers operation were experimentally determined with the aid of the Taguchi methods. On this subject, the initial conditions of the experimentation were set as follows: the grease amount used (0.16 g) for one guideway and its initial thickness (30 μm); as well as, the table speed of the grease distribution device (1100 mm/min). Moreover, the experimentation was restricted to the following measuring intervals (hours): 0.5, 1, 2, 5, 10, 15, 20, 25, 30, 35 and 40. During these intervals, the amount of accumulated grease mixture Q_g in the outside rollers and the thickness of the grease layer T_g over the guideways were measured. As a result, it was possible to determine the relationships between all the parameters involved, the amount of accumulated grease mixture in the external rollers and the change in thickness of the grease layer throughout time. Particularly, the operation conditions that were obtained correspond to the material of the rollers, the diameter of the rollers and the contact load with respect to the slider as shown in Table 1. Nevertheless, in order to measure the effectiveness of the obtained operation conditions, in this research just the set of the best and worst experimental conditions are going to be evaluated. In this regard, the entirety of the experimental data and further explanation about it can be consulted in a parallel research [7].

Accordingly, the amount of accumulated grease Q_g and the grease layer thickness T_g behavior of the best and worst operation conditions are compared in Fig. 5. Firstly, it can be observed that the grease layer thickness T_g of the worst conditions experiment becomes very thin right after the first hours of operation and a presents a small amount of accumulated grease Q_g. Hence, this lubrication regime would need another device to supply enough grease. Meanwhile, the W-rollers with the best specifications exhibit a considerable amount of accumulated grease Q_g and a steady grease layer thickness T_g behavior. Consequently, a clear tendency that supports the initial hypothesis is observed.

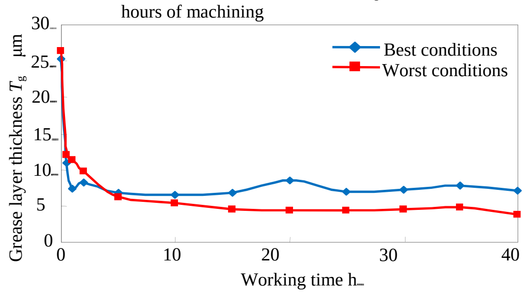
Finally, the "Double-ECO model" is applied to this technology through the application of several science fields. Specifically, the manufacturing process involves the mechanical engineering field, while the application of Polyethylene oxide PEO_{-8} corresponds to the chemical engineering field. Consequently, this makes the technology an environmentally-friendly and affordable one by reducing parameters that involve higher costs.

Table 1 Comparison of optimum machining specifications obtained using the Taguchi methods.

Control factors		W-rollers with the best specification	W-rollers with the worst specification
W-rollers		Yes	Yes
Outside roller	Material	Cloth	Polyester
	Diameter	ϕ20 mm	ϕ25 mm
	Load	14.5 N	0.0 N
Inside roller	Material	NBR	Polyurethane
	Diameter	ϕ20 mm	ϕ25 mm
	Load	14.5 N	49.0 N



(a) Amount of accumulated grease (Q_g) after 40 hours of machining



(b) Change of the grease layer thickness T_g

Fig. 5. Relationship between the working time and the amount of accumulated grease Q_g and the grease layer thickness T_g

3.2. Development of a forced cooling method using mist of strong alkaline water for restraining thermal deformation on a machine tool

The cutting fluids [8] or MQL (minimum quantity lubrication) [9] are commonly used for forced cooling during multiple processes. However, most cutting fluids pollute the environment and most MQL agents cooling performance is inferior to other cooling alternatives. In this research, a forced cooling method using a mist of strong alkaline water for restraining thermal deformation on a machine tool was developed and evaluated for only cooling effect. Additionally, among the reasons to choose strong alkaline water are that it shows a pH value above 12.5, has high interfacial permeability, dissolving, emulsification, and separation properties. Furthermore, after multiple corrosion tests of different machine tool components and materials for up to 2 months, it was observed that most components did not corrode under the influence of strong alkaline water. In contrast, it had a very large cooling effect because vaporization of the mist occurred due to the heat involved. Thus, mist of strong alkaline water was supplied around the structure of the machine tool and the machining area, in order to restrain the thermal deformation and alleviate the heat generation during machining. Accordingly, a bench lathe and a CNC milling machine were used for the experimentation. In the first instance, thermal deformation of the bench lathe was measured to evaluate the forced cooling effect that the mist of strong alkaline water possesses. Subsequently, the effects of mist of strong alkaline water were also evaluated with respect to the tool temperature during cutting, surface roughness and the tool life parameters on a CNC milling machine [10]. In this regard, the entirety of the experimental data and further explanation about it can be consulted in a parallel research [10]. Furthermore, the existing relationship between the heat transfer coefficient and the mixture ratio of air and strong alkaline water is shown in Fig. 6. In this case, the length *L* from output nozzle to measuring point was 225 mm. Moreover, the parameter considered here is the total flow rate of strong alkaline water. There are two plots in this figure; one is the mist condition (fine strong alkaline water) which has very large forced cooling effect because of the heat of vaporization, and the other one is the fluid condition (fine air pockets) which has a very large heat transfer coefficient because it presents a high speed.

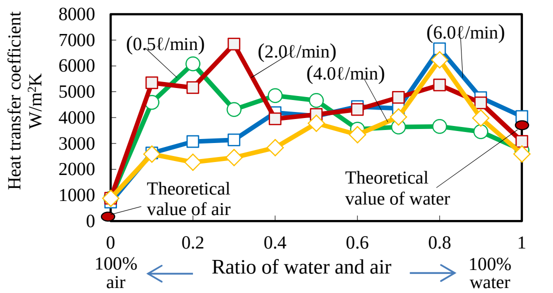


Fig. 6. Relationship between the heat transfer coefficient and the mixture ratio of air and strong alkaline water

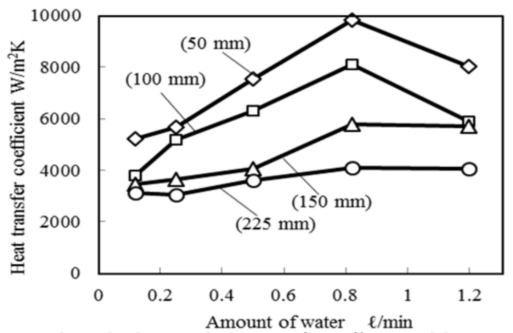
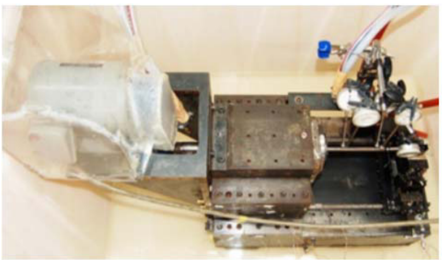
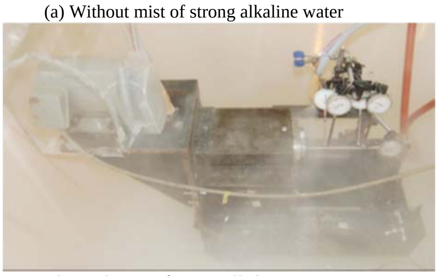


Fig.7. Relationship between the heat transfer coefficient and the optimum amount of air and strong alkaline water



(a) Without mist of strong alkaline water

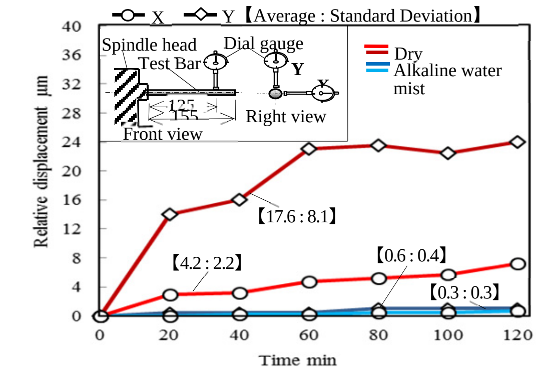


(b) With mist of strong alkaline water

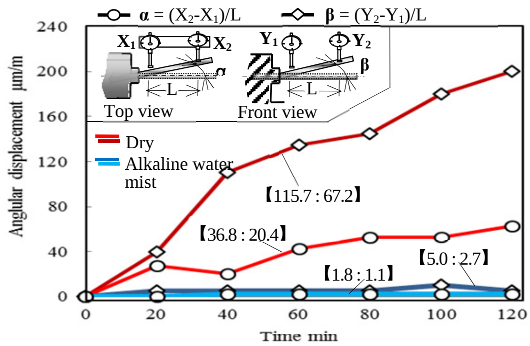
Fig.8. Photographs of the experiments

The relationship between the heat transfer coefficient and the optimum amount of air and strong alkaline water is shown in Fig. 7. The parameter considered here is length *L* mm from output nozzle to measuring point. When the distance (*L*) becomes smaller, the heat transfer coefficient becomes larger. In this figure, there is a peak in each plot near 0.8 ℓ/min of total flow rate of strong alkaline water, and when amount of air is 113.3 ℓ /min, the total flow rate of strong alkaline water is 0.82 ℓ /min. At this point, the distance *L* mm from output nozzle to measuring point is 50 mm, and the heat transfer coefficient is about 10000 W/m^{2}K. These results clearly show that the forced cooling using mist of strong alkaline water has a very strong influence. Thus, it can be said that the thermal deformation of structure can be effectively cooled by using a mist of strong alkaline water.

The relative displacement (X and Y directions) and angular displacement (α and β directions) of the tip of test bar measured at operation a speed 3600 min^{-1} are shown in Fig. 9. In the same way, the data between 20 min to 120 min were divided into 6 intervals and the average values and standard deviations of each of the six intervals are plotted. The results show that, in dry cutting, relative displacements are large with ΔX=6.0μm, ΔY=24.0 μm and angular displacements were α=55 μm/m and β = 200 μm/m, in mist of strong alkaline water, the relative displacements are ΔX=0.6 μm, ΔY=0.9 μm and angular displacements are α=3.6 μm/m and β=9.0 μm/m. This means that, when operated under a mist of strong alkaline water, the thermal deformations due to operation speeds reduced significantly. However, since standard deviations are very small in this case, temperature changes are also very small and therefore thermal behaviour highly stable.



(a) Relative displacement



(b) Angular displacement

Fig. 9. Thermal deformation of the bench lathe in strong alkali water mist at 3600min^{-1}

These results clearly show that relative displacement and angular displacement were restrained by using mist of strong alkaline water and showed a very strong influence. Therefore, it can be said that by using mist of strong alkaline water in bench lathe, the thermal deformation of machine structure can be effectively suppressed and resulting in a high machining accuracy.

On the other hand, changes in the tool life during machining under a mist of strong alkaline water were evaluated. Cutting conditions for tool life test are shown in Table 2. Similarly, the results of the tool life test were shown in Fig. 10 and dry cutting and oil wet cutting were also shown for reference. It was observed that that the tool life of the tool using mist of strong alkaline water was 2.5 times of one of dry cutting and 1.4 times of one of wet cutting with only oil respectively. Hence, it is thought that a mist of strong alkaline water is an effective method for extending the tool life during machining. To support this, in the case of the cutting using mist of strong alkaline water, defects were not observable in the microscope.

In addition, surface roughness test results are shown in Fig. 11 and dry cutting and wet cutting with only oil were also shown for reference. After machining, surface roughness on the workpiece using mist of strong alkaline at limit of tool life water was 22 % of one of dry cutting and 50 % times of one of wet cutting with only oil respectively. Surface roughness on the workpiece using mist of strong alkaline at start of the test is similar to that of dry cutting and wet cutting with only oil. However, a mist of strong alkaline water is

Table 2 Cutting conditions for tool life test

Cutting conditions			
Cutting speed 100 m/min	Feed/ tooth 0.15 mm/tooth	Width of cut 3 mm	Depth of cut 2 mm
Work piece			
Material : S50C			
Tool (Endmill with 2 throw away tips)			
Rake angle: 5°		Coated carbide	

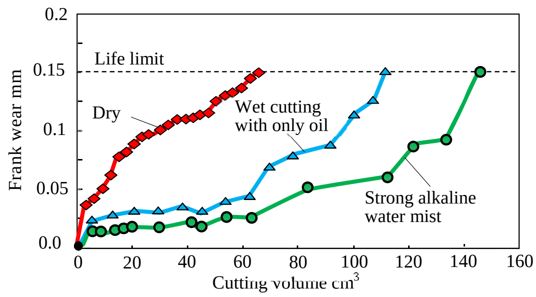


Fig. 10. Results of tool life test

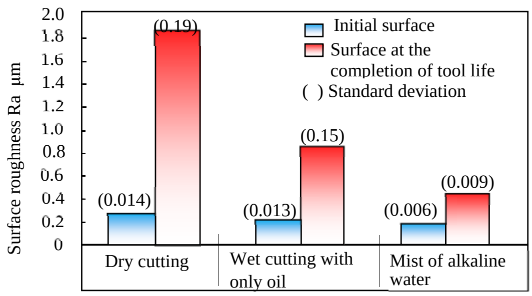


Fig. 11 Surface roughness results

thought to be an effective method for the improvement of surface roughness on the workpiece. Thus, it can be said that by using practice CNC milling machine with mist of strong alkaline water, the heat generation for cutting can be effectively removed; resulting in a low tool temperature, long tool life and fine surface roughness.

Lastly, regarding the “Double-ECO model” being applied to this particular research, manufacturing tools that correspond to the mechanical engineering field were the main part in this research. Nevertheless, a deep understanding of the thermodynamics field was also necessary to evaluate the water evaporation effect. Similarly, the alkaline water mist employed in this research also made use of the chemical engineering field. In the end, this makes the technology an environmentally-friendly and affordable one by reducing parameters that involve higher costs.

4. Evaluation and considerations for the presented Double-ECO model technologies

Since the developed technologies were created to support the intensity of production at a low-environmental impact level with the highest cost-effectiveness, in this section both the environmental and economic aspects of the “Double-ECO model” technologies will be assessed. In the first instance, the proposed model evaluates the degree of how “environmentally-friendly” a technology is through the CO_2 emissions involved. On the other hand, the economic aspect of the presented technologies will be based on a general overview of the technical requirements involved in each research.

4.1. Evaluation of the “development of a cost-effective and environmentally-friendly permanent grease lubrication for machine tool sliders” technology

Firstly, the environmental impact of this technology will be assessed based on a comparison of the amount of exhaust CO_2 using the proposed and conventional lubrication. This was calculated through a simple Life Cycle Analysis (LCA) and real data from “OM Machine Tools Ltd”. Considering that a Large lathe uses 55kW (main motor) and 38 ℓ/year of lubrication oil; and that a small lathe uses 37kW (main motor) and 26 ℓ/year of lubrication oil, exhaust CO_2 (kg- CO_2) generation for 1 year was calculated by the equation (1) [11].

$$\text{Exhaust } CO_2 = 3.44\times10^{-2}\times W_0+2.62\times L_0 \qquad (1)$$

Where, W_0 (ℓ) is the amount of waste oil and L_0 (ℓ) is the amount of light oil used for conveyance. Here, L_0 was defined as 0 (ℓ), and the results are shown in Fig. 12. In Fig. 12 we can also appreciate that, conventional machine tool needs abundant lubricant oil for smooth drive and high accuracy positioning. Moreover, most of it is wasted and introduced into the environment. In contrast, the proposed method only requires a small amount of grease mixture (<< 1(ℓ)), a low cost device, and does not waste or release oil into the environment. Therefore, within one year, the amount of exhaust CO_2 for the machine tool with the proposed lubrication was about one-fortieths (≒ 1.29÷0.03) of the

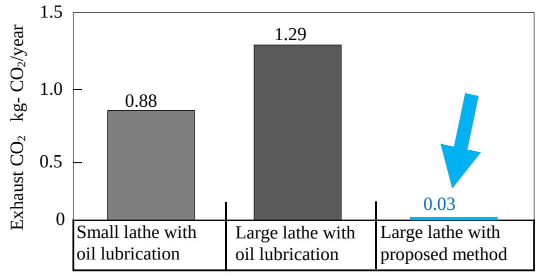


Fig. 12. Comparison of exhaust CO_2 of the proposed permanent lubrication and the conventional lubrication (Environment)

Table 3 General overview of the proposed permanent lubrication and the conventional lubrication expenses (Cost-profit)

Lubrication method	Proposed lubrication	Conventional lubrication
Friction coefficient	0.01 ◎	0.17 ×
Initial cost	Polymer ○ W-roller ○	Pump ○
Running cost	Neglectable ◎	Oil supply × Electricity ×
Maintenance	Little ◎	Need ×
Remarks	Low-environmental impact and profitable	High-environmental impact

◎ : Excellent, ○: Good, ×:Weak

conventional lubrication. The new grease and the W-rollers can be described as excellent for being almost "Emission free" and "Environmentally-friendly".

Finally, a comparison between the expenses involved in the proposed lubrication and the conventional lubrication is shown in Table 3. It is possible to conclude that the proposal is more affordable, given that the initial costs would be dramatically less; as well as a neglectable running cost of maintaining the lubrication regime. Thus, the "Double-ECO model" goal of simultaneously reaching a "highly cost-effective" and "environmentally-friendly" technology is achieved.

4.2. Evaluation of the "development of forced cooling using mist of strong alkaline water for restraining thermal deformation on a machine tool" technology

Firstly, the environmental impact of this technology will be assessed based on a comparison of the amount of exhaust CO_2 using the proposed and conventional cooling. This was calculated through the relationship between the electricity consumption per hour and the CO_2 emissions. For this, it was considered that the electricity used by the coolant pump on the milling machine during conventional wet cutting was 1.2kW per hour and a working year being composed of 250 days and 8-hours per day. Furthermore, the amount of CO_2 emissions, CL_{CO2}, is calculated by using the equation (2).

$$CL_{CO2} = 0.468 \times W_E \quad (2)$$

Where, W_E is the amount of used electricity (kWh) used in coolant pump and 0.468 the conversion value for kg-CO_2/kWh.

The corresponding calculated amount of CO_2 emissions for the coolant pump is 1123.2 kg-CO_2. Subsequently, the amount of CO_2 emissions due to the oil disposal was calculated. In

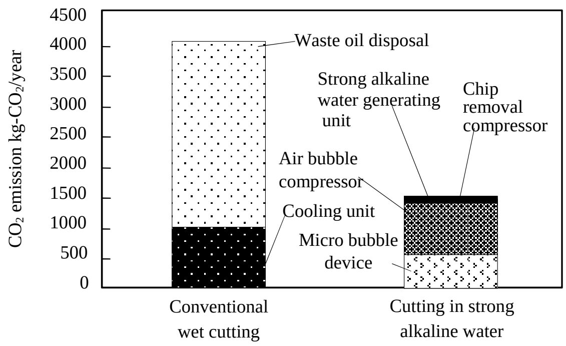


Fig. 13. Comparison of CO_2 emissions (Environment)

this case, the amount of oil is assumed to be 340 L and disposal times to be 2 times/year a year. However, milling machines require a monthly oil fill-up which is assumed to be 30 ℓ a month (30 ℓ × 12 month=360 ℓ). Hence, the total amount of disposed oil was assumed to be 1040 ℓ and the CO_2 emissions were calculated based on this value and using the equation (3)

$$CO_2\,\textit{emission}\ (\text{kg-}CO_2) = \textit{Disposed oil}\ \text{k}\ell \times \textit{Emitted heat energy}\ \text{GJ/k}\ell \times \textit{Carbon emission}\ \text{t-C/TJ} \times (44 \div 12) \quad (3)$$

Where, the emitted heat energy is 40.2 GJ / kℓ and the amount of carbon emission is 19.22 t-C / TJ, and by using equation (2), the amount of CO_2 emission due to disposed oil was calculated and a value of 2946.3 kg-CO_2 was obtained. Therefore, the total amount of CO_2 emitted from both cases was 4069.5 kg-CO_2. Furthermore, the comparison between the conventional wet cutting method and the proposed method is shown in Fig. 13.

In contrast, the amount of CO_2 emissions of cutting in strong alkaline water mist can be reduced to 2634.9 kg-CO_2, (64.7 % reduced) in a year. This is due to the less power consumption for the cooling of the tool; as well as, the lower emissions that represent not using cutting oil in the proposed method. Thus, it can be considered that this method is not only effective in cooling the machine tool but also capable of reducing the impact to the environment.

Table 4 General overview of proposed cooling and the conventional cooling expenses (Cost-profit)

Cooling method	Proposed cooling	Conventional cooling
Cooling capacity	Very large ◎	Average △
Initial cost	Alkaline water ○ Pump ○	Refrigerator ×
Running cost	Oil supply × Electricity ×	Oil supply × Electricity ×
Maintenance	Little ◎	Need ×
Remarks	Low-environmental impact and profitable	High-environmental impact

◎ : Excellent, ○: Good, ×:Weak

Ultimately, a comparison between the expenses involved in the proposed cooling and the conventional cooling during machining is shown in Table 4. It can be noted that the proposal is more affordable, given that the initial costs would be considerably less because of the low market price of alkaline water. Thus, the “Double-ECO model” goal of simultaneously reaching a “highly cost-effective” and “environmentally-friendly” technology is achieved.

5. Conclusions

From this research, the following was possible to conclude; (1) There is a need of the general approach that the “Double-ECO model” defines, since a common “Economy” and “Ecology” niche has not been developed as a method for the benefit of humankind and the environment (2) The application of the “Double-ECO model” into real production engineering problems and technology is proposed and presented in the “Cost-effective and environmentally-friendly grease lubrication” and “Forced cooling using mist of strong alkaline water” researches. (3) It was concluded from the experimental results of these technologies, that improvements in the environmental pollution, mechanical properties and cost parameters were achieved through the proposed model.

References

[1] Tanabe I. and Hong M. T., Cutting with an environment-friendly cooling method using water evaporation, Transactions of Japan Society of Mechanical Engineers, Vol. 67 No.664, Series C, August 2001, pp. 4011–4016(in Japanese).

[2] e-Gov Japan, Ordinance related to calculation for carbon dioxide equivalent greenhouse gas emissions with their business activities of specified emitters, Article 2 (2013), available from < http://law.e-gov.go.jp/htmldata/H18/H18F15002002003.html> (accessed on 22 April, 2014) (in Japanese).

[3] Tanabe I., Truong H. M., Yoshii K., Turning with environment-friendly cooling method using water evaporation, Transactions of the Japan Society of Mechanical Engineer, Series C, 2000, Vol. 66, No. 643, pp. 1026-1030(in Japanese).

[4] Tanabe I. and Truong H. M., “Cutting with an environment-friendly cooling method using water evaporation” , Trans. of Japan Society of Mechanical Engineers, in Japanese, Vol. 67 No.664, Series C, August 2001, pp. 4011–4016.

[5] Tanabe I., Yamanaka K., Mizutani J. and Yamada Y., A new design of lathe structure for reducing thermal deformation (Design of zero-center on three directions, self-compulsory cooling and design of thermal synchronism), Transactions of Japan Society of Mechanical Engineers (Series C), Vol. 65, No.639, (1999), pp. 4508-4513 (in Japanese).

[6] Tanabe I., Ye H. S., Iyama T. and Abe Y., Control of tool temperature using neural network for machining work-piece with low thermal conductivity, Transactions of Japan Society of Mechanical Engineers (Series C), Vol. 77, No.776, (2011), pp. 1556-1564 (in Japanese).

[7] Tanabe I. and Watanabe M., Development of Cost-effective and Eco-friendly Permanent Grease Lubrication for the Machine Tool Slides, Proc. of ISAM 2011(IEEE) in Tampere, (2011) ,pp. 1-6

[8] Shintani S., Hand book for cutting fluid, Kogyo Chosakai Publishing Co., Ltd., (2004), pp. 33-48 (in Japanese).

[9] Okada M., Hosokawa A., Asakawa N., Fujita Y. and Ueda T., Influence of minimum quantity lubrication on tool temperature in end milling of difficult-to-cut materials having low thermal conductivity, Transactions of Japan Society of Mechanical Engineers (Series C), Vol. 78, No.792, (2012), pp. 3093-3103 (in Japanese).

[10] Tanabe I., Development of forced cooling using mist of strong alkaline water for restraining thermal deformation on a machine tool, MM-science journal, DECEMBER , (2014), pp. 521-526

[11] Enviroment agency, “Law (enforce No3) for Global Warming Countermeasures in Japan-(Exhaust coefficient list),” 2006.